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The 1992 NASA Communications Technology Program at JPL

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The goals of the NASA Communications Technology Program at JPL are to develop technologies to enhance future space telecommunications systems in support of NASA science needs, and to maintain and support the U.S. communications satellite industry. The scope of activities at JPL ranges from development of concepts of advanced communications systems and propagation effect studies to design of critical subsystems such as antennas, codecs and modems and field testing of communications terminals.

The purpose of this article is to review the activities JPL plans to carry out in fiscal year 1992 (October 1991–September 1992). Systems concept and propagation studies are focused on spectrum- and power-efficient communications techniques and low rate (2.4–9.6 kbps) mobile terminals. The program includes the development of a mobile terminal, which is to be field tested with the Advanced Communications Technology Satellite (ACTS). ACTS, operating at 20 and 30 GHz, is planned for launch in early 1994. Another technology development area is optical communications, oriented toward support of future data transmission requirements for NASA deep space missions. JPL has been active for a number of years in supporting development of the L-band Mobile Satellite System, and this technology is now being transferred from NASA to industry. JPL will be completing its involvement with a Direct Broadcast Satellite–Radio experiment and demonstration using the MARECS-B2 satellite. An important activity is the transfer of information on NASA-developed technology to industry, which includes the publication of the *SATCOM Quarterly* and sponsoring professional meetings and symposia.

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The Satellite Communications (SATCOM) Program is managed by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration. The goals of this Program are to develop advanced system concepts and technologies in the areas of mobile, micro and personal communications. A major thrust of the Program through the mid-1990s is the development of the mobile terminal to operate with NASA's Advanced Communications Technology Satellite.

Advanced Studies

The overall goal of this task is to define innovative satellite-based communications systems concepts for NASA communications development programs. The objectives of this element of the program are to provide long term direction to the JPL SATCOM technology development effort,

utilize the NASA investment in programs such as MSAT-X and propagation studies and provide a stimulus to and support of U.S. industry. The approach used in carrying out this element of the program is to review the long term direction of SATCOM system applications and to develop innovative system approaches to meet the needs of these applications. Examples of the efforts carried out under this task are personal communications studies and the direct broadcast of audio programs by satellite.

During 1992, this task will develop definitions of mid- and long-range communications satellite trends and industry technology needs. This will be accomplished through literature surveys, meetings with U.S. and foreign industrial organizations and interaction with NASA and industry technologists. The most promising satellite-based communications system concepts, including land-mobile satellite, aeronautical satellite, personal and satellite/terrestrial hybrid communications systems, will be examined. Technology needs which may lead to more efficient spectrum and orbit utilization, easier channel access and lower cost user terminals will be identified. A prioritized list of promising technologies and system concepts, and a plan for developing these technologies, will be generated.

This task is being funded by the NASA Office of Commercial Programs and is being led at JPL by Arvydas Vaisnys.

ACTS Mobile Terminal

The overall objective of this task is to evaluate the potential of K- and Ka-bands to meet the needs of future personal and mobile satellite services and to develop critical technologies required to implement those evaluations. The benefit of this activity is that it will enable realistic demonstrations of the use of Ka-band in mobile communications applications. This task will consist of developing enabling technologies for a Ka-band land-mobile and aeronautical test-bed. Technologies being addressed include high gain K- and Ka-band vehicular antennas and the development of robust communications strategies for K- and Ka-band channels.

This task was started at the beginning of fiscal year 1991. During the first year, significant progress was made in the design and implementation of the system. By the end of September 1991, the system design had been completed and the construction of critical subsystems was well under way. This includes the development of breadboard models of the reflector antenna, the antenna and terminal controllers, the modem and codecs. A preliminary design review was completed in February 1991, and the critical design review was completed in December 1991.

The major milestones planned for this fiscal year are the completion of all major subsystem development and the initiation of subsystem integration. Specifically, these subsystems include the following:

- Complete reflector antenna system testing and begin integration with the antenna pointing mechanism in March 1992.
- Complete testing of integrated antenna control and the integrated RF and IF up- and down-converter chassis in July 1992.
- Complete testing of the speech codecs, terminal controller, modem and data acquisition system by the end of September 1992. In addition, the development of data analysis software will begin in this month.
- Begin system integration and system laboratory testing in October 1992.

These milestones will lead to the completion of integration and laboratory testing by April 1993. This will be followed by the installation of the completed system into a JPL van and the initiation of trials with the ACTS satellite beginning the same month.

This task is jointly funded by the NASA Office of Applications and Space Technology and the NASA Office of Commercial Programs. It is being carried out by a team led at JPL by Thomas Jedrey.

Optical Communications Technology

The objective of this task is to develop technologies required to implement free-space high rate data links with an emphasis on deep space communications needs. The benefits of optical communications for deep space spacecraft are higher data rates and reduced spacecraft mass, size and power requirements. The use of coherent phase-locked optical reception, an important part of the JPL program, provides superior background noise rejec-

tion. The approach being used in this task is to characterize frequency-stabilized lasers and demonstrate phase-coherent optical heterodyne receiver technology. Another element of this task is the development of high rate (10–100 Mbps) optical phase modulators. In addition, advanced composite materials are being applied to optical communications subsystems to provide lightweight, yet stable, optical benches.

Specific plans for 1992 include

- Development and characterization of a 532-nm laser transmitter with 2-W average output power, a 50-kHz pulse repetition rate and overall power efficiency of 3%.
- Development of technologies required to define a configuration which is lightweight and has high thermal and structural efficiency. This will be accomplished by incorporating a laser transmitter subsystem utilizing advanced composite materials.
- Development of component and subsystem technology that will enable the demonstration of a coherent optical receiver for free-space optical communications. A specific objective will include the completion of a high data rate (100 Mbps) laboratory system to demonstrate heterodyne spatial tracking.
- Development and testing of technologies to enable acquisition and tracking of extended source targets under conditions expected in deep space optical communications systems. This will include developing algorithms to track a simulated Earth disk, which will include varying illumination and cloud conditions on the disk as viewed from space. Hardware will be developed to implement an acquisition and pointing system, with provision for inducing mechanical vibrations of the type anticipated in the deep space environment.

These tasks will be carried out to meet a long term objective of developing a breadboard — and eventually a flight model — of a spacecraft optical communications terminal.

The Optical Communications task is being funded by the NASA Office of Applications and Space Technology and is being carried out by a team led by Dr. Jim Lesh.

Radio Frequency Propagation Studies

The objective of the JPL Propagation Studies task is to carry out propagation research to enable new, and enhance existing, applications in Earth/space communications. The benefit of this activity is that it enables new wide band communications systems technologies such as signal transmission at higher frequency bands, mobile satellite communications and direct broadcast of audio programs via satellite. In addition, this effort provides propagation data models to engineering communities and technical data to regulatory bodies. The approach to this task is to carry out propagation experiments and studies in the 12-, 20- and 30-GHz bands using signals from the Olympus and ACTS spacecraft, and at 90 GHz using radiometers. The results of this work will be transferred to user organizations through seminars and workshops.

The NASA Communications Technology Program at JPL supports the transfer of NASA-developed technology to industry.

In 1992, the following propagation studies efforts will be carried out by university contracts:

- Propagation observations will be made at 12 GHz using an INMARSAT beacon to complete the collection of low elevation data, which have been collected for the previous two years by the University of Texas. A large scale diversity study will be carried out at 20 and 30 GHz using actual weather data to define the resource needs of the ACTS satellite under diverse weather conditions. An ACTS Data Center will be set up at the University of Texas to archive ACTS propagation data.
- A first-year report on 12-, 20- and 30-GHz propagation measurements using the Olympus satellite was published in December 1991. A second year of data will be collected and published near the end of next year. This task is being carried out under contract by the Virginia Polytechnic Institute and State University.
- A review of the COST 210 program will be carried out and presented to the International Radio Consultative Committee (CCIR) in May 1992.

A map-based rate climatology will be developed for use by the CCIR in October 1992. This task will be carried out by Dartmouth University.

- A study of rain attenuation measurements in New York and Virginia will be completed. A new measurement campaign will take place in Oklahoma using 20- and 30-GHz radiometers, and one will be carried out in the Madeira Islands using 20-, 30- and 90-GHz radiometers. These sites have been chosen by a set of criteria that includes elevation angle, weather diversity and infrastructure availability. This effort will be carried out by the National Oceanic and Atmospheric Administration.
- A study will be completed by the University of California, San Diego, on fade predictions and mitigation, with a final report due in September 1992.
- JPL will carry out the development of propagation software models, will advise NASA on the development of the ACTS propagation terminals and will make contributions to the CCIR deliberations on mobile satellite propagation as part of in-house efforts.

The Propagation Studies task is being funded by the NASA Office of Commercial Programs and is led by Dr. Faramaz Davarian.

ACTS Experiment Development

The objective of this task is to understand the performance of ACTS for mobile- and microterminal experiments and to aid the ACTS Experiment Program Office in developing an experimenter base for these applications.

This task will be carried out by

- Assisting potential experimenters in understanding the ACTS system and providing them with technical assistance in developing experiments. This will involve briefing potential experimenters about ACTS, providing help in the development of experiments and facilitating the creation of industrial partnerships to perform experiments of interest to NASA and the industrial partner. This activity is being closely coordinated with NASA Lewis Research Center.
- Defining the specifications for an ACTS terminal to be located at JPL and defining experiments to be carried out in the Los Angeles area using this terminal.
- Supporting the design of aeronautical and maritime experiments to be conducted with ACTS.
- Providing staff support to the ACTS Experiment Office at NASA Lewis Research Center and the ACTS Experiment Program Office at NASA Headquarters.

This task is being funded by the NASA Office of Commercial Programs and is led by Dr. Polly Estabrook.

Mobile Communications Technology

This task element includes several activities, including support to the NASA Mobile Satellite System experiments program, development of a geostationary satellite environment handbook and performing technology transfer activities. The objective of the technology transfer task is to implement the transfer of NASA-developed technology to U.S. industry to maximize its utilization. The benefits of this activity are that it enhances the competitiveness of U.S. industry, enables full utilization of NASA's technology development investment and facilitates the interchange and refinement of ideas among members of the satellite communications community. The approach to this task includes publishing the *SATCOM Quarterly* and maintaining a library of technical reports and documents for distribution to the U.S. SATCOM community. This task also includes the initiation and support of technical conferences, and briefings and technical consultation to government agencies.

These tasks are being funded jointly by the NASA Office of Commercial Programs and the NASA Office of Applications and Space Technology.

Summary

The NASA Communications Technology Program at JPL will carry out a broad range of activities in fiscal year 1992 to enable advanced space telecommunications systems. These activities include advanced communications systems and propagation effect studies, the development of critical subsystems for optical and mobile satellite communications and the development and field testing of mobile communications terminals.

DBS–R Successfully Demonstrated

Laura C. Steele, SATCOM Quarterly Managing Editor
Jet Propulsion Laboratory

Demonstrations of the first radio broadcasts by satellite were held recently by the Direct Broadcast Satellite–Radio (DBS–R) Program, which is a joint effort by NASA and the United States Information Agency's Voice of America (VOA). The demonstrations proved the feasibility of satellite–radio broadcasts to a wide audience. The attendees included U.S. Government agency personnel, the ambassadors of a number of nations and members of the satellite industry and the press.

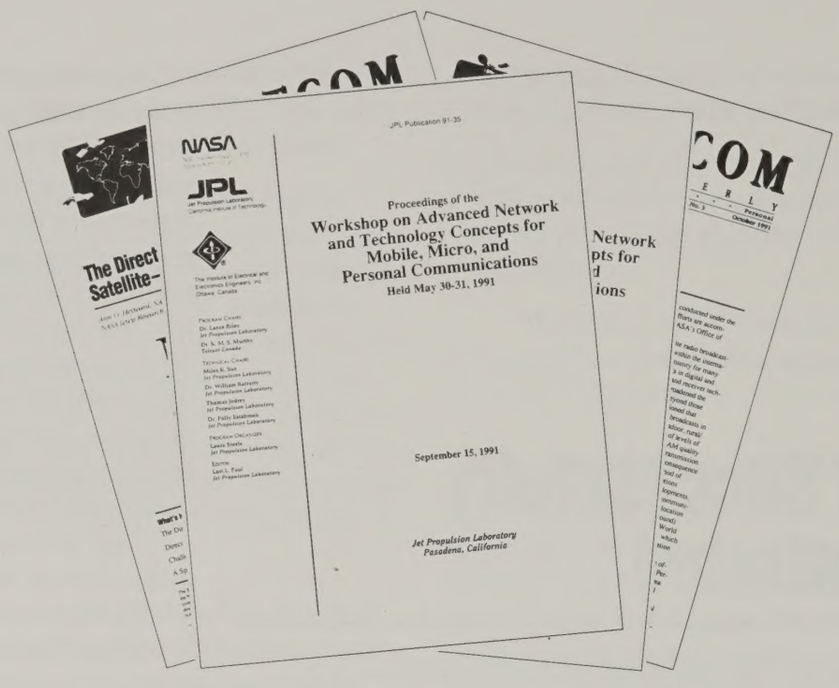
The demonstration was conducted using the COMSAT Earth Station in Southbury, Connecticut; INMARSAT's MARECS-B2 satellite; programming from National Public Radio, and a mobile terminal developed by JPL and installed in a passenger van. During the week of December 2–6, 1991, the demonstration took place at the Hotel Washington in Washington, D.C. Attendees listened to a brief presentation and then saw a video describing DBS–R technology development and the equipment involved. They were then invited to listen to the satellite–radio broadcast in the van as it drove around the Washington Mall area.

According to James Hollansworth, DBS–R Program Manager at NASA's Lewis Research Center, DBS–R service opens up opportunities for industry to provide a new generation of satellites, antennas, receivers and programming options. The response from demonstration participants supported this statement and indicated enthusiasm about the new technology. Ambassadors and representatives from international embassies in the United States were particularly interested in applications of direct broadcast satellite technology and indicated their intention to pursue digital audio broadcasting by satellite for their own countries.

In February 1992, the 164-member International Telecommunications Union will convene the World Administrative Radio Conference (WARC) in Málaga/Torremolinos, Spain. At this time, nations will consider frequency requirements for a Broadcast Satellite Service BSS (Sound). A frequency allocation in the radio spectrum for BSS (Sound) will enable DBS–R systems to be implemented by the late 1990s. The DBS–R demonstration system may be transported to Spain in order to support a frequency allocation for digital audio broadcasting by satellite during the 1992 WARC.

For more details about the DBS–R Program and technology development efforts, see the October 1991 issue of the *SATCOM Quarterly*.

A range of DBS–R services may be available by the late 1990s.



New SATCOM Publications

New documents are available from the JPL SATCOM Publications Office:

New Documents

Proceedings of the Workshop on Advanced Network and Technology Concepts for Mobile, Micro and Personal Communications

The workshop was held May 30–31, 1991, at the Jet Propulsion Laboratory. Request JPL Publication 91-35 (334 pages).

Wireless Communications Market Overview and Analysis: An Assessment of the Market Opportunities for PASS Technology

The document was produced for JPL in September 1991 by the Gartner Group. Approximately 320 pages, it is available for distribution only within the United States. Request SATCOM Publication 201.

Communications and Propagation Experiments Using the Olympus Spacecraft — Report on the First Year of Data Collection

The document was produced for JPL in October 1991 by the Virginia Polytechnic Institute and State University. Request SATCOM Publication 202 (275 pages).

MSAT-X Technical Briefs

The following nine briefs, produced in 1985, are three to four pages each. Request a set of MSAT-X technical briefs.

Medium Gain, Electronically Steered, Conformal Phased-Array Vehicle Antenna

Medium Gain, Mechanically Steered, Tilted-Array Vehicle Antenna

Vehicle Antenna Pointing Techniques for Mobile Satellite Applications

Low Cost Omnidirectional Vehicle Antennas for Mobile Satellite Communications

Near-Toll-Quality Digital Speech at 4800 bps

Coded Modulation for 4800–9600-bps Transmission in a Fading Mobile Satellite Channel

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Propagation Experiments to Model the Mobile Satellite Channel

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Market and User Analysis for Personal Satellite Communications

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Wireless communications technologies, including cellular phones, mobile satellite service and mobile radio, are expected to completely alter the present telecommunications infrastructure. Advances in technology are moving the wireless communications industry from "press-to-talk" mobile radios and cellular phones with limited service areas toward universal personal communicators which provide two-way voice communications from any location in the world.

Personal access satellite systems (PASS), which are highly portable, self-powered, toll-quality voice communication devices, will have certain competitive advantages and disadvantages as they enter the wireless communications marketplace. These characteristics will determine the share of individual markets PASS will be able to win from other communications technologies. To learn more about which individual markets PASS will compete most effectively in, and what equipment characteristics are desired by those markets, a "Market/User Analysis for PASS Technology Study" was undertaken by the Gartner Group under JPL's sponsorship.

The Gartner Group study was divided into three tasks. The first task involved identifying potential markets for PASS. The list of markets included a discussion of factors which would affect the demand for PASS and the competition for these markets from present and proposed communication technologies. The second task was to survey members of these markets. Participants were asked to indicate the characteristics they sought in a communication system and their willingness to pay for the service. The third task involved the integration of these findings, providing information on the markets to which PASS might be well suited, the overall size of each market and the characteristics needed to compete effectively in these markets.

Market Opportunities

The world market for telecommunications products in 1989 was estimated at $193 billion. The market share for wireless communications products was $11 billion, or about 6%. Based on historical trends and technological advances in communications products in general, the total telecommunications market is projected to grow at roughly 12% annually, to $391 billion in 1995. The share of this market belonging to wireless communications products will grow to over 10%, or $38 billion, reflecting a growth rate of nearly 22%. Although PASS is not expected to enter the market until the next century, these numbers illustrate the lucrative potential for wireless communications products.

Driving these projections are the advances being made in communications products such as cellular phones, and opportunities that are evolving from the availability of wireless communications products. Table 1 lists some of those opportunities that might some day represent market opportunities for PASS. The reader is cautioned that the market size estimates are very speculative in nature.

These market opportunities exist because of the capability of wireless communications products to increase the use of information in many of our activities. These products will provide the ability to

- Communicate with, and know the location of, mobile equipment and personnel
- Communicate with and share large databases with field locations
- Establish communications with remote locations
- Provide a temporary communications link that does not depend on local electrical power
- Continuously update central databases to track field operations

Table 1. Estimated number of terminals per prospective PASS market.

Market	Market size (thousands)
Retail operations	
Fast food franchise management	210
Gas station management	1,700
Small retail, point of sale, credit verification	13,000
Banking — ATM networks	270
Transportation	
Long haul truck fleet management	9,000
Less than truck load trucking fleet management	11,000
Train control	40
Train boxcar monitoring	5,000
Train cargo tracking	20,000
Field operations	
Utility data collection	300,000
Sales/field service support	8,000
Field maintenance service for complex technology	6,500
Insurance — e.g., disaster site claims processing	700
Oil platform control	3
Construction survey crew communications	8
Public safety	
Fire and ambulance service	275
Telemedicine	260
Disaster/emergency services	500
Law enforcement — remote operations	1,800
University/campus services	500
Remote site communications	
Pipeline monitor	100
Environmental/remote area monitors	24,000
Home/business security	112,000

Consumer Perspective

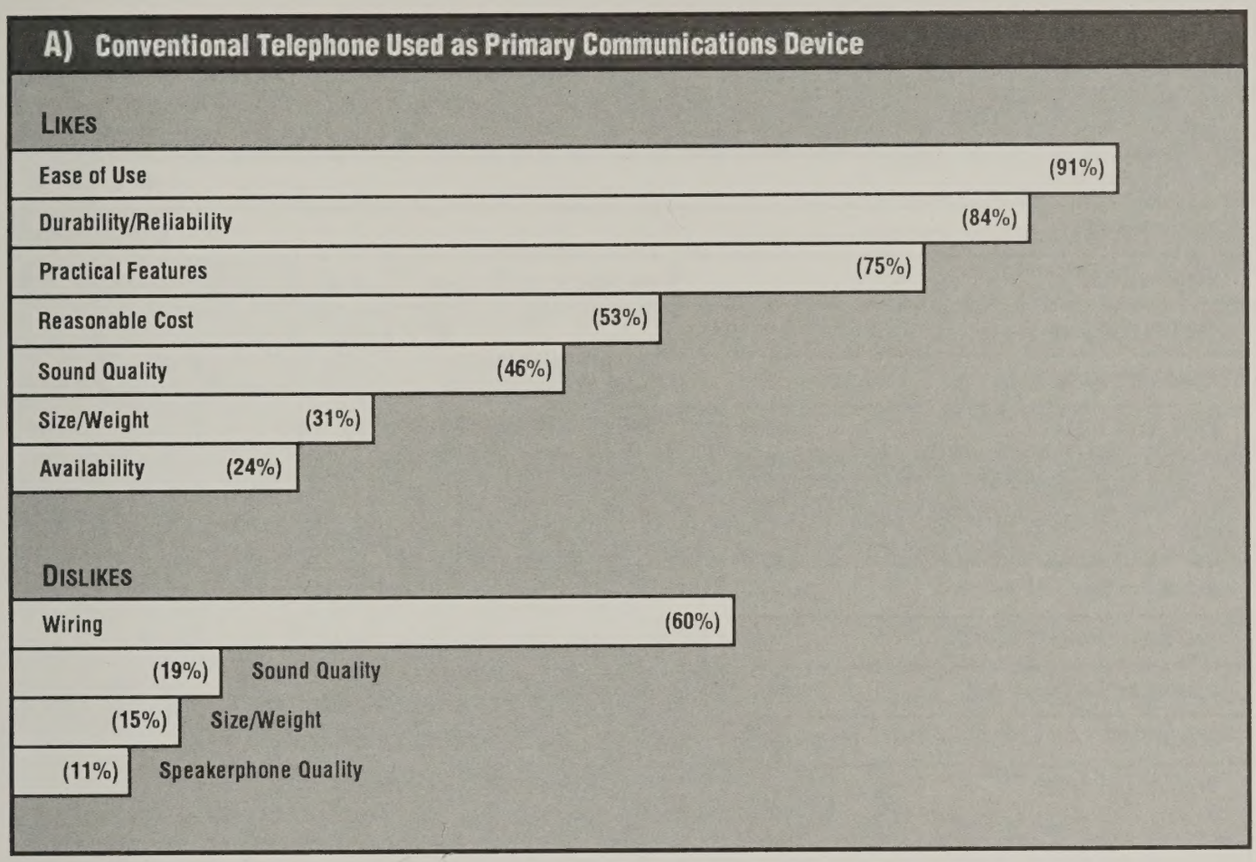
Designing communications systems to serve these markets requires an understanding of the characteristics sought by consumers. To obtain this information, representatives from major industries and Federal and local government were surveyed. Approximately 350 individuals were surveyed by personal and telephone interviews. The majority of respondents (85%) indicated that the conventional telephone was their primary communication tool and that cellular phones were secondary. The majority of the remaining respondents met their communication needs with a combination of mobile radio and telephone.

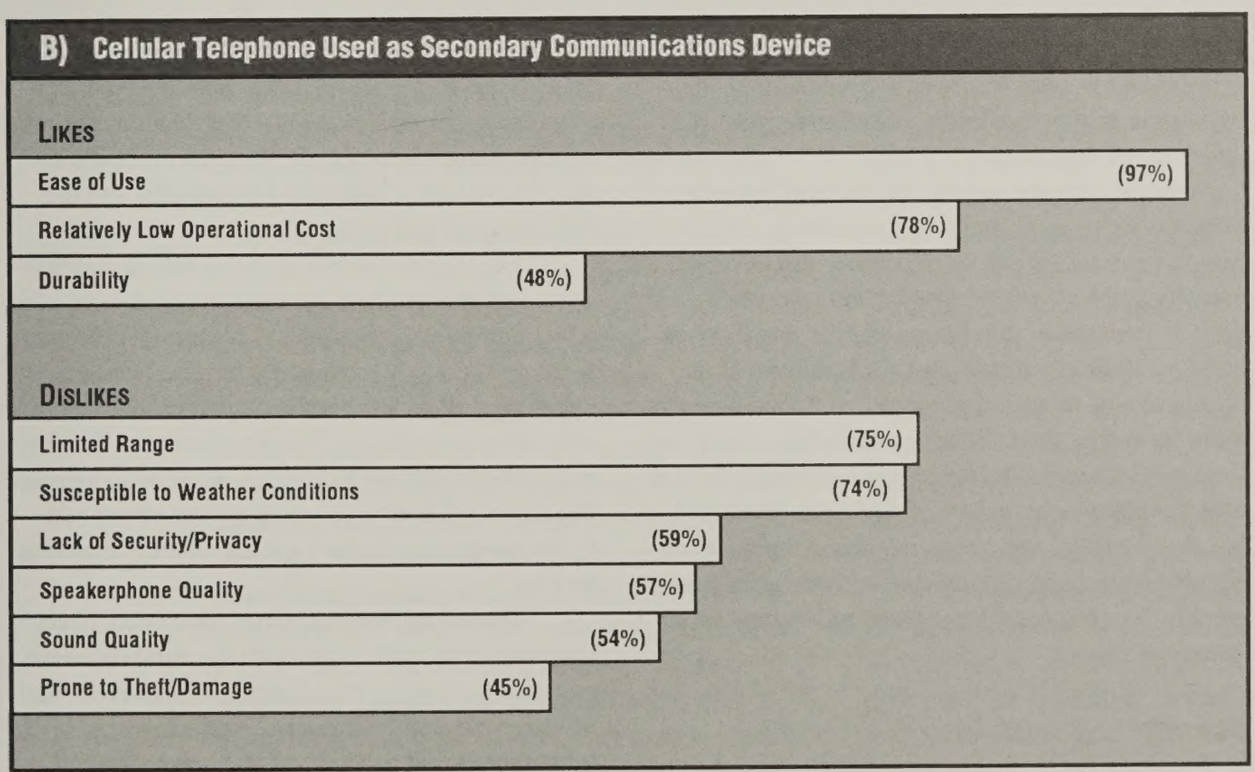
Responses to the question "What do you like and dislike about the terminal handset in use?" are summarized in Figures 1A–C for three different categories of respondents. For those surveyed whose primary communications device was a conventional telephone, characteristics that appealed to most users were the ease of use, durability and reliability, as well as features such as automatic redial and hands-free operation. Also, a significant number felt that the cost was reasonable and the sound quality was good. On the other hand, 60% of the respondents disliked the fact that the unit was attached to the network by a wire.

For those using cellular phones as a secondary means of communication, desirable characteristics included mobility and ease of use, followed by digital display, other practical features, durability and price. Dislikes included sound quality, as well as the low signal power and battery limitations of portable cellular phones.

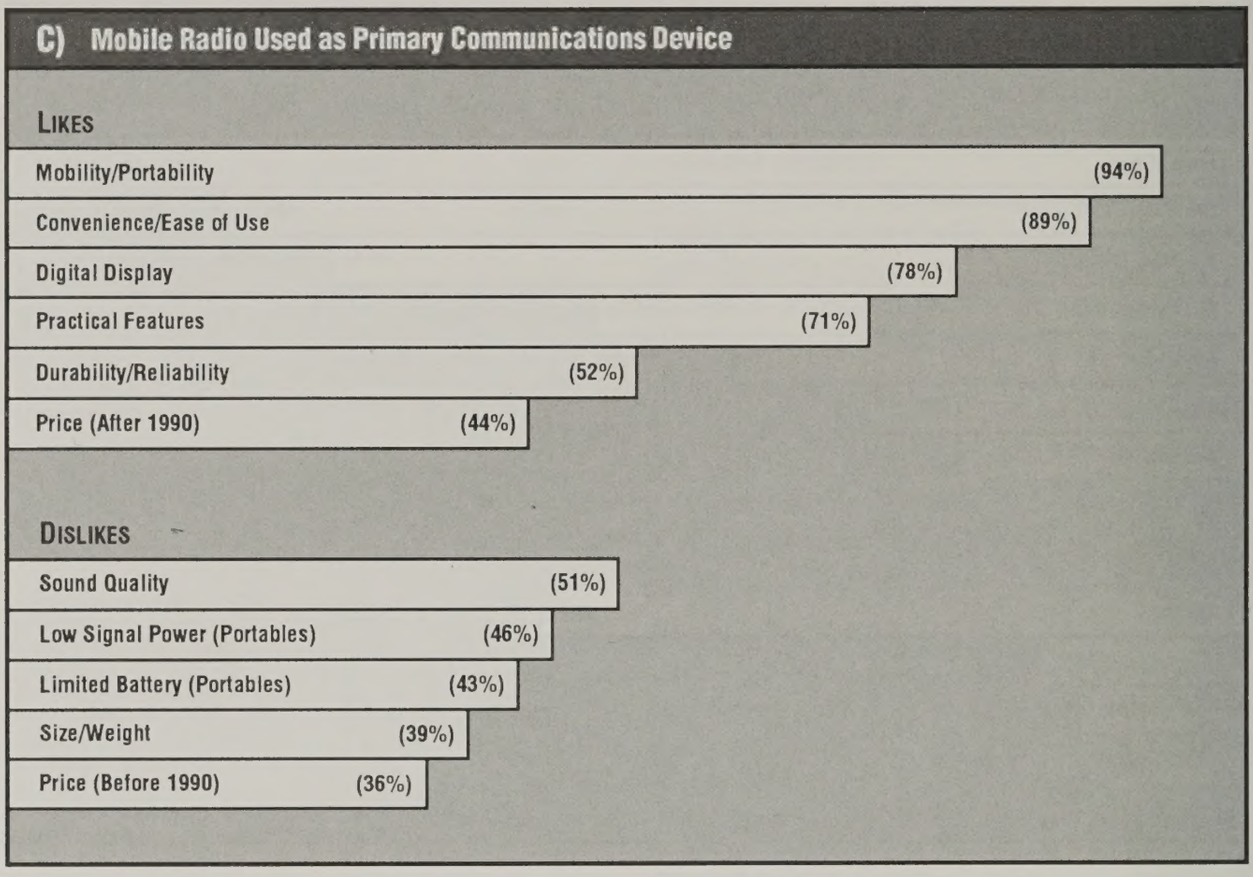
Those who used mobile radio as their primary communications system also indicated that ease of use, low operating cost and durability were characteristics that they liked. However, their principal dislikes were different from the first two groups: limited operating range, susceptibility to weather and other sources of interference and lack of security and privacy.

Responses to a second question — "How much would you be willing to pay monthly for the use of a small hand-held phone that you could carry with you and use from any location?" — indicated that cost could significantly limit PASS technology's ability to capture market share. Among those using telephones for primary communications, 51% indicated they would not be willing to pay more than $50 a month for the terminal and basic service. This percentage rose to 73% at $70 a month and 96% at $90 a month. However, their actual cost experience suggests that they may be willing to pay more. For those using telephones as their primary mode of communications, 59% had monthly bills of $200 or more. For those using mobile radios for primary communications, monthly bills for most users ranged from $300 to $500. Monthly bills for cellular phones were more modest; a large majority





Figures 1A–C. Results of consumer survey: "What do you like and dislike about the terminal handset in use?"



of these bills were in the $100 to $200 range. Lower cellular phone costs mirrored the secondary role these phones play in meeting telecommunications needs for those surveyed.

Separating the survey respondents into the principal categories contained in Table 1 — transportation, retail, public safety, home and business security and field services and sales — revealed little differences in the pattern of likes and dislikes because of the dominant use of telephones. However, in terms of the respondents' cost experiences, there were significant differences. Public safety and field services and sales sectors had distinctly higher bills for their primary service while the home and business security sector had the lowest costs. A reasonable explanation for this pattern relates to the need or lack of need for mobility and frequency of communications.

Summary

The size and growth of the market for wireless communications provides exceptional opportunities for PASS technology. Although the use of conventional telephones still dominates telecommunications in most sectors of the market, the general dislike of wiring suggests that opportunities exist for more mobile telecommunications services. Leading candidates for mobile communications services include public service agencies and the field services and sales sector.

The biggest barrier faced by PASS technology is the competition for these markets from other telecommunications products. Winning a share of these markets will most likely require competitive prices as well as technical advantages that would be offered by an evolving PASS technology. Survey respondents indicated a clear reluctance to increase their terminal and basic service costs above relatively modest levels for a mobile communications service.

The survey indicated that consumers liked characteristics such as ease of use, durability and practical features in their handsets. However, they were not pleased with several characteristics of cellular phones and mobile radios, such as limited range and sound quality. Paying attention to these consumer concerns should help PASS someday capture a significant share of the telecommunications market.

A Low Cost, Conformal Antenna and Tracking System for Mobile Satellite Service

Arthur C. Densmore, Antenna Systems Engineer
John Huang, Antenna Engineer
Jet Propulsion Laboratory

In the early 1980s, the Mobile Satellite Experiment (MSAT-X) project commenced at JPL to develop capabilities for, and demonstrate the feasibility of, commercial mobile satellite service using L-band frequencies. A major area of the research was the development of antennas and their associated pointing systems. The goal here was to optimize the antennas for mobile operation, yet keep them economical so as to encourage commercial applications. To date, MSAT-X experiments have demonstrated the use of such antenna systems by communicating via satellite with a vehicle traveling on freeways between Santa Barbara and Los Angeles, California; driving on residential streets in Pasadena, California, that were lined with heavily foliaged trees, and traveling between Sidney and Brisbane, Australia. The latter demonstration was done in conjunction with Australia's AUSSAT organization [1]. These field trials made use of a van which was equipped at JPL to serve as a mobile laboratory. The van also contained equipment to record data during the experiments to allow detailed postexperiment analysis. The purpose of these experiments was to study and characterize the performance of mobile satellite systems as an aid to emerging commercial markets.

As reported in [2], the JPL MSAT-X mechanically steered antenna had been revised to reduce its height from 9 to 6 in. The revision involved a substantial reduction in the height of the platform which supported the antenna element, but the use of a tilted microstrip patch array antenna element that was itself about 5 in. high limited the overall height reduction. In the conclusion of [2], a novel concept to further reduce the antenna height from 6 to 1 1/2 in. was reported. Called the Conformal Yagi-Array concept, it could dramatically reduce the overall height because it utilized a flat, horizontal array of microstrip patch elements and thus took full advantage of the platform height reduction.

The latest version of the MSAT-X Mechanically Steered Vehicular Antenna System (MSVAS) does in fact implement the Conformal Yagi-Array concept; the tracking algorithm has also been revised to reduce the pointing jitter by an order of magnitude. In order to minimize the overall height, all of the antenna's auxiliary RF circuitry was integrated onto a single-layer board only 1/8 in. thick, called the beamformer. The MSVAS can actually accommodate any array antenna that is suitable for an MSAT-X mechanically steered application, but a low overall profile is best achieved with thin planar arrays that are mounted horizontally, such as the Microstrip Yagi [3,4] or the ANSERLIN [5]. Both of these arrays utilize a simple, flat microstrip construction, but to date only the Microstrip Yagi has been incorporated into the MSVAS.

The MSVAS consists of two interconnected assemblies: one that mounts to the roof of the mobile vehicle and to which is mounted the antenna and beamformer, and a second assembly that provides the computer-controlled satellite tracking function and is installed inside the vehicle. Both of these assemblies are identified in the mobile terminal block diagram of Figure 1. The former assembly consists of both the *antenna and beamformer* and *motor and rotary joint* blocks in the figure, and the latter assembly is the *antenna pointing system* block. Well suited to mass production, the MSVAS with a planar, conformal microstrip array antenna, such as the Microstrip Yagi, is of a simple, sturdy overall construction, making it durable for use in the mobile environment.

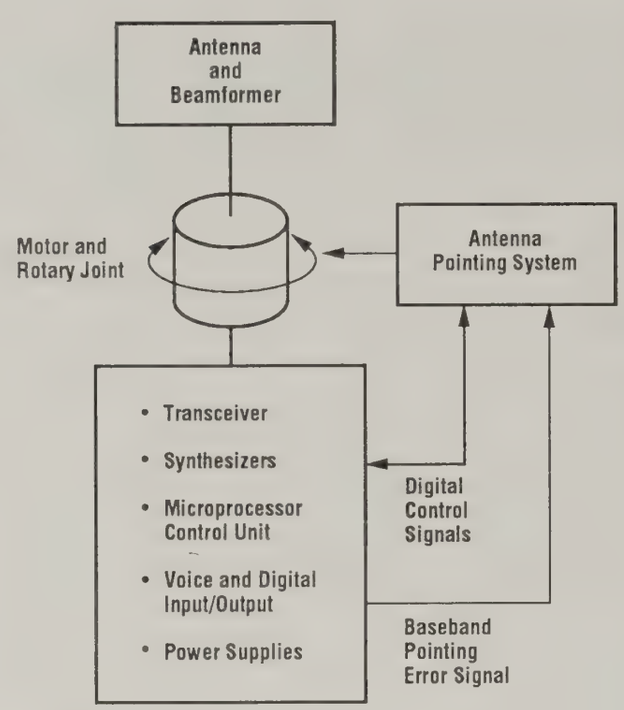


Figure 1. MSAT-X mobile terminal block diagram.

Vehicle Roof-Mounted Assembly

The MSVAS roof-mounted assembly consists of the antenna, a stripline microwave circuit called the beamformer, a motorized turntable platform (which steers the antenna azimuth angle) and the radome cover. This whole assembly, with the Microstrip Yagi array incorporated as the antenna, is shown with a clear radome in Figure 2. The overall height of this assembly is only 1 1/2 in. The planar microstrip array and stripline beamformer are bonded together (the large rectangle under the radome in Figure 2) and are the components which are rotated in order to point toward the satellite. The rotating and stationary components of the assembly are connected through a single-channel, coaxial rotary joint. The MSVAS uses the same reduced-height platform design reported in [2], but with some modifications. Slip rings are not used since all DC is passed to the antenna circuitry directly through the rotary joint; this significantly reduces the friction and thus the torque required of the motor. The central bearing assembly was also modified to further reduce the overall height.

The Microstrip Yagi array of microstrip patch elements is prominent in Figure 2, and its design is discussed in detail in [3,4]. It is fabricated on a single, rectangular piece of 1/4-in.-thick substrate. Since the great majority of mass of the array is its rectangularly shaped substrate and not the copper electroplate, the array is inherently balanced when squarely mounted on the motorized turntable. The Microstrip Yagi array has an azimuth beamwidth of about 30 deg, and broad elevation coverage (20–60 deg from the horizon) which allows operation anywhere in the continental United States. The antenna/beamformer gain varies from 9.5 to 14.5 dB over the 20–60-deg elevation range. Over the same elevation range the system receive sensitivity (G/T) varies from –15.3 to –10.3 dB/K.

Not only does the antenna array provide MSAT-X terminal communication via the satellite, but it is also used by the tracking system to sense antenna pointing error. Monopulse pointing error detection is used, whereby any phase difference between the satellite tracking beacon received by the right and left halves of the array is detected to yield an estimate of the magnitude and sign of the pointing error. This detection is one of the functions of the beamformer.

The beamformer is a stripline microwave circuit which is only 1/8 in. thick and is bonded flush to the underside of the antenna array; direct feedthrough pins make the connections between the RF beamformer circuits and the antenna array. A single-channel coaxial rotary joint connects to the center of the beamformer from the bottom; this one coaxial channel is its only electrical connection to the rest of the system and is used to distribute RF and DC signals between the rotating array/beamformer assembly and the stationary base, which is mounted to the roof of the vehicle. The functions of the beamformer are to 1) distribute transmit energy from the rotary joint to the array, 2) collect the receive energy from the array and distribute it to the rotary joint and 3) detect any antenna pointing error and modulate the error signal (monopulse) for subsequent demodulation and use by the tracking system to compensate for the error. For the Yagi Array MSVAS system, the monopulse antenna pointing error detection slope is $M = 1.20$/rad, or 0.021/deg.

The beamformer microwave circuit is shown in Figure 3. Compared to the previous MSAT-X system reported in [2], the latest version MSVAS beamformer has several improvements. Previously, the antenna's auxiliary RF components (beamformer circuits) consisted of individually packaged components cabled together on the rotating antenna platform and powered through DC slip rings from the stationary base, and some of the components

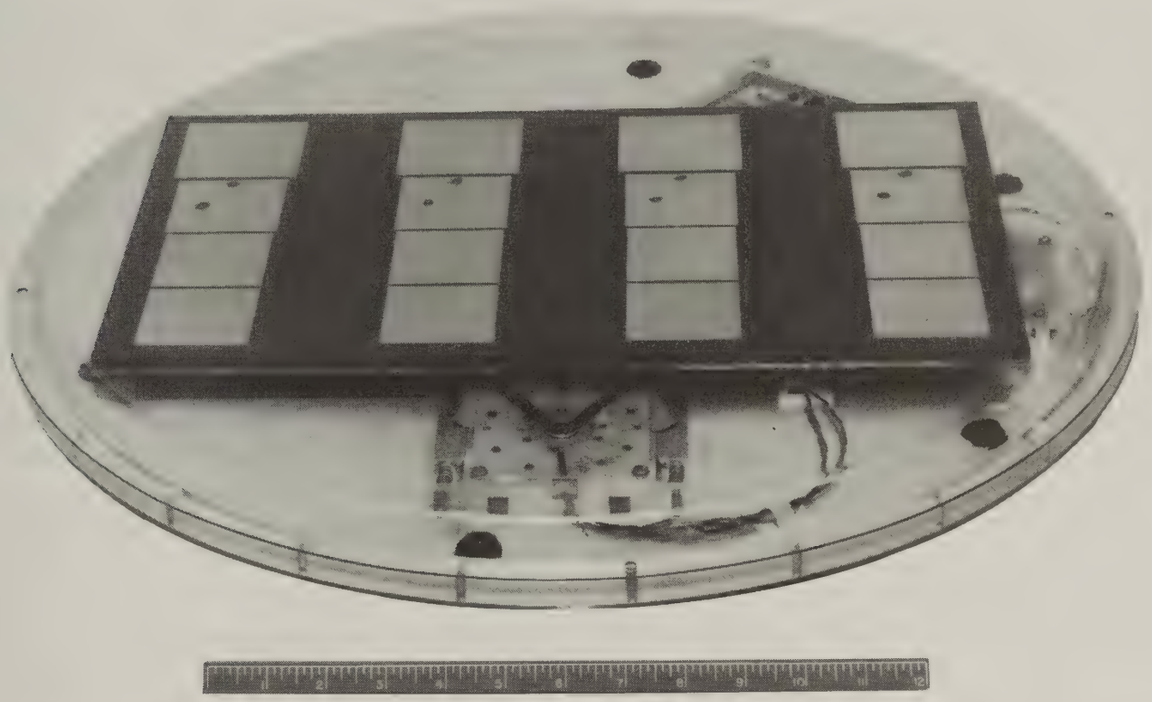


Figure 2. MSVAS roof-mounted assembly with Microstrip Yagi array antenna.

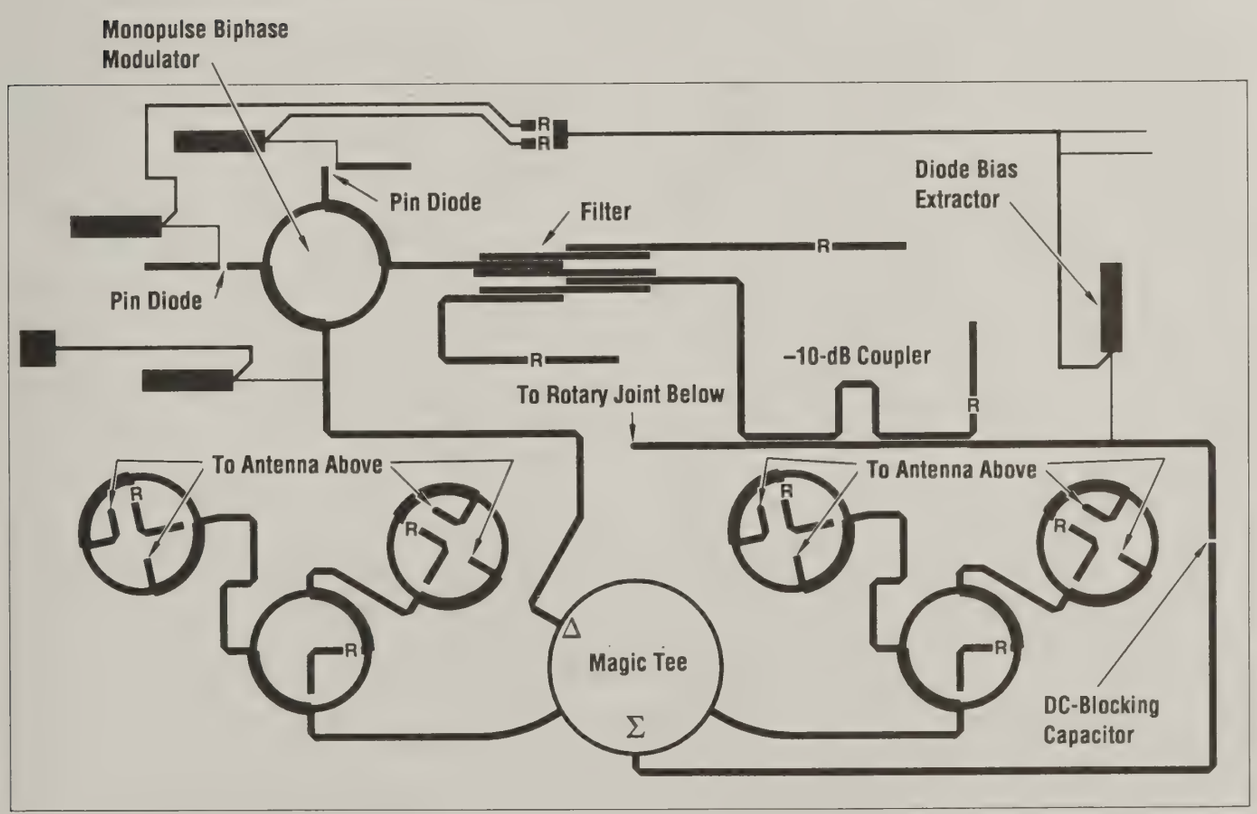


Figure 3. Stripline beamformer circuit.

were as tall as 1 in. This new version beamformer has *all* the RF components integrated into a single, thin (1/8 in.) package, and without the need for DC slip rings to supply power. Essential in achieving this integration were three innovations in the beamformer RF design. The first was the replacement of a bulky ferromagnetic isolator in the previous design with a negligibly thin, simple stripline resonator filter, seen in the top center of Figure 3. The second innovation was the development of a stripline phase modulator that could fit completely within the 1/8-in.-thick beamformer assembly and also solve a high-transmit-power intermodulation problem experienced by the previous design, as reported in [6]. The third innovation was to utilize the beamformer RF line to carry all DC power and control lines required by the phase modulator through the coaxial rotary joint as well as the RF, which allowed the removal of the slip rings.

Satellite Tracking System

The MSVAS satellite tracking system controls the antenna pointing direction to keep the antenna oriented toward the satellite while the vehicle moves about. Only one-dimensional (azimuth) tracking is required since the antenna elevation coverage is wide enough for operation anywhere within the continental United States. The antenna pointing system uses pointing error information obtained from the beamformer as the source of feedback to ascertain correct pointing; a tracking beacon is sent from the satellite specifically for this function. The variance of the pointing error estimate depends on the signal-to-noise ratio (SNR) of the detected tracking beacon. Noise in the radio channel becomes random movement, or jittering, of the antenna. The MSVAS tracking system described here is an improved revision to an earlier implementation, described in [7–10].

Almost all that is required of the pointing system is to compensate for the yaw rotation of the vehicle. Since geostationary satellites are so far away, the direction toward the satellite as seen from the vehicle effectively doesn't change unless the vehicle turns. An inertially stabilized tracking system would be suitable. Once the direction to the satellite is known, a high-performance gyro mounted to the frame of the vehicle could accurately inform the antenna pointing system where to aim the antenna to remain accurately pointed toward the satellite as the vehicle moves about. Since MSAT-X's objective is to develop an economical system, such high-performance gyros are not used; instead, low cost inertial turn-rate sensors are employed. (A magnetic compass could not be used because of the local perturbations in magnetic field caused by metallic structures such as bridges and other vehicles.) The low cost rate sensor tends to accumulate a significant pointing error after only a moderate period of time, so it is used in conjunction with the antenna monopulse pointing error signal simultaneously in the tracking system.

By the use of a planar microstrip array, the MSVAS antenna height has been reduced to only 1 1/2 in.

After 30 sec, the total integrated rate sensor error is a few degrees of vehicle yaw, and only a small bandwidth of feedback of the monopulse antenna pointing error signal is required to completely make up for these rate sensor errors. By minimizing this bandwidth to only that sufficient to correct for the rate sensor errors, the pointing system's sensitivity to noise and fading effects induced by the radio channel is minimized; this gives the pointing system a kind of inertia to free-wheel through radio signal outages which corrupt the monopulse antenna pointing error signal. A monopulse pointing error feedback bandwidth of 0.1 Hz is sufficient to compensate for the rate sensor errors. A second-order feedback system is implemented so that temperature-induced variations in the rate sensor's bias may be completely compensated in the steady state; if a first-order system were used, as was in the previous MSAT-X tracking system reported in [7–10], ovenization would be required to fully stabilize the rate sensor bias drift induced by temperature and vehicle vibration; such bias represents a ramping pointing error if not compensated.

Figure 4 shows the flow diagram of the antenna tracking control system. θ_V is the yaw angle of the vehicle with respect to Earth, and θ_A is the azimuth angle of the antenna with respect to the ve-

hicle, so θ_E is the antenna pointing error, since the satellite is geostationary. Pointing information is obtained both from the vehicle yaw rate sensor and the antenna monopulse signal. The full bandwidth (10 Hz) of the rate sensor signal is used as (open loop) feed-forward compensation of vehicle turns, but only a small bandwidth (the control loop noise bandwidth, $B_N = 0.1$ Hz) of the monopulse signal is used as (closed loop) feedback to keep the antenna locked in the direction of the satellite. Use of such a small bandwidth is possible because the vehicle yaw rate sensor provides, in the short term, a nearly error free source of pointing information. The control system integrates the vehicle yaw rate measured by the rate sensor and uses this (open loop) information to directly compensate for vehicle motion by turning the antenna the same amount as the vehicle turned, but in the opposite direction. The closed loop Laplace transfer function and closed loop, single-sided noise bandwidth B_N of the pointing control system are given below. $J(s)$ is the pointing jitter transfer function of the antenna motor rotation angle caused by noise in the monopulse pointing error estimate signal and is deduced directly from Figure 4 using Mason's Rule for signal flow graphs [11].

$$J(s) \doteq \frac{\theta_A(s)}{\sigma_N(s)} = \frac{(K + G/s)/s}{1 + MK/s + MG/s^2} \qquad (1)$$

$$B_N \doteq \frac{1}{2\pi|J(0)|^2}\int_0^\infty |J(j\omega)|^2 d\omega = \frac{KM + G/K}{4} \qquad (2)$$

The pointing system is an inherently stable second-order system as long as M, K and G are positive valued, and it is characterized by two time constants: 1) $\tau_1 = 1/B_N$ is the approximate system response time to monopulse pointing error signal changes, and 2) $\tau_2 = K/G$ is the system response time to compensate for variations in the bias of the vehicle yaw rate sensor. Values of $\tau_1 = 10$ sec and $\tau_2 = 32$ sec (a power of two; see the implementation discussion that follows) were used, yielding $K = 0.33$ sec^{-1}, and $G = 0.01$ sec^{-2} for the Yagi Array MSVAS system.

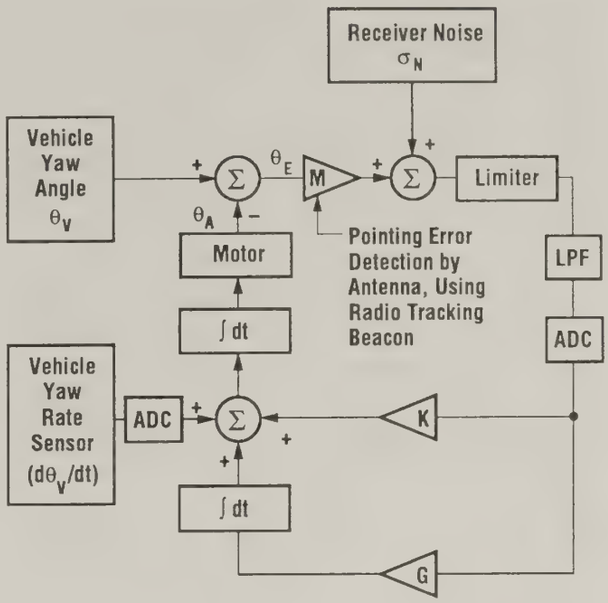


Figure 4. Antenna pointing control system block diagram.

Figure 4 diagrams a continuous-time system even though the implementation is digital and only updated at periodic, discrete-time intervals. The rate at which the digital system cycles, 113 Hz, greatly exceeds the maximum bandwidth of the system, which is the 10-Hz vehicle yaw bandwidth detected by the rate sensor, and so it is suitable to analyze the discrete-time control system using continuous-time techniques. The discrete-time implementation flow graph is found from the continuous-time equivalent, Figure 4, by using the s-to-z transform: $1/s = T/(1-1/z)$, where T is the discrete-time interval. The computer which implements the antenna tracking function solves a system of differential equations according to Figure 4. The MSVAS uses an economical 6502 microprocessor with a 1-MHz clock rate and software written in assembly language. A microprocessor interrupt occurs 113 times per sec, and each time through the interrupt service routine the rate sensor and monopulse signals are sampled, the system state variables are updated and the stepper motor is stepped if required. The sample rate, or microprocessor interrupt rate, is chosen such that the scaling required in addition to the accumulation of each integration step is an integer power of two; this reduces the integration scaling to simple shifting of the binary point and helps the pointing system interrupt routine, implemented on the 6502 CPU, to complete in less than 1/113 sec. The shift of a binary point requires far fewer clock cycles than an

integer multiplication or divide routine, not to mention floating point arithmetic. The pointing error signal is limited in magnitude by the limited voltage range of the monopulse detection output circuitry and then bandlimited to $B_1 = 50$ Hz to prevent aliasing, prior to sampling by the analog-to-digital converter (ADC).

The rms antenna pointing jitter σ_p is given by $\sigma_p^2 = B_N/\text{CNR}/M^2$; the pointing control loop acts as a simple filter transferring noise from the radio channel into random, rotational movement of the antenna. The recent MSAT-X field trials experienced a receive signal-to-noise power spectral density of CNR = 40 dB-Hz nominally; for this case the pointing jitter was about 0.2 deg. With 10-dB signal fades (CNR = 30 dB-Hz), the pointing jitter was about 0.5 dB. The previous MSAT-X antenna tracking system, described in [7–10], required the use of a closed loop bandwidth 100 times greater (10 Hz) and experienced pointing jitter 10 times greater (2-deg rms at 40 dB-Hz, and 5-deg rms with 10-dB fades) than those of the current system. Pointing jitter is not significant unless its magnitude approaches about one-third the antenna azimuth beamwidth, or unless the pointing jitter is simply too great for the mechanical drive system; MSAT-X experience suggests that pointing jitter any greater than 5-deg rms is unacceptable.

The Microstrip Yagi MSVAS, incorporating a planar antenna array and a satellite tracking system, is a low cost, low profile system that has performed well in the mobile environment.

MSVAS Field Tests

The MSVAS has been used in several field tests over a period of several years and has proven durable in the mobile vehicle environment.

In August 1990, the MSVAS using the Microstrip Yagi array was completed and used in the JPL Multipath Rejection Measurement Experiment (MRMEx) to evaluate the advantage medium gain antennas have compared to low gain antennas in reducing the amount of multipath interference received [12]. A MARISAT satellite (106.5° W) beacon at 1541.5 MHz was tracked and a variety of propagation conditions were encountered. From the Los Angeles area the satellite was seen at about 22 deg east of south at an elevation angle of 47 deg. The experiments involved installing the MSVAS in the JPL mobile-laboratory van and driving along freeways and residential roads in the Los Angeles area. Routes that included a range of light to moderate shadowing were used. The particular routes taken were a 3-mile residential loop encircling the Rose Bowl in Pasadena, a 3-mile residential street lined with densely foliaged trees in Pasadena (traveled in both directions) and a 30-mile freeway loop in the San Gabriel Valley area. The nominal received tracking beacon CNR was 41 dB-Hz, and the MSVAS performed flawlessly throughout the experiment.

More than a year after construction and use in MRMEx, and without the need for any adjustments, the Microstrip Yagi MSVAS was unboxed, installed on a van and used for a series of experiments and public demonstrations held in Connecticut and Washington, D.C., in late 1991 in support of the Direct Broadcast Satellite–Radio (DBS–R) work conducted by JPL [13]. DBS–R is the distribution of high quality digital audio directly from satellite to mobile or fixed systems. The Microstrip Yagi MSVAS again performed flawlessly.

Conclusion

The MSVAS, together with a planar antenna array such as the Microstrip Yagi, provides a good balance of the practical features required of an antenna system for mobile satellite service and has been demonstrated to perform very well in actual field trials. It is a low cost, low profile, medium gain and high efficiency system and has proven sufficiently durable in the mobile environment. JPL has plans for continued use of the Microstrip Yagi MSVAS in the next few years to support DBS–R and other L-band mobile satellite applications.

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A Stochastic Rain Fade Control Algorithm for Satellite Link Power

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The ACTS Rain Attenuation Prediction Model [1] was developed in response to several system design and performance requirements of satellite systems in and above 30/20 GHz (Ka-band), most notably NASA's Advanced Communications Technology Satellite (ACTS), after which the model is named. Two major model requirements are the ability to estimate signal fade due to rain on a satellite link using, in the general case, attenuation measurements that may be corrupted with random as well as systematic measurement errors (defined here as *identification*) and, secondly, the ability to predict what such attenuation levels will prevail a short time into the future so as to forewarn the need for a fade countermeasure (defined here as *prediction).*

For example, the user of a small remote satellite terminal may employ the received communications channel, with all its attendant power fluctuations due to modulation, etc., as the source of measurement of link attenuation due to rain to drive some fade mitigation technique, the use of which is needed beyond some preestablished fade threshold. Or, as in the case of ACTS, one may be operating at a frequency that is not only impaired by rain but also by the phenomena of clear-air and/or cloud scintillation; here, one receives the total fading signal and, if one is to have a reliable satellite communications link, one must separate out the component rain and scintillation effects since each must be dealt with in a different manner (e.g., rain fade by power control and scintillation — if it proves to be a problem — by time diversity transmission).

It is the purpose of this article to indicate how results of the dynamic portion of the ACTS Rain Prediction Model can be used in the implementation of processing schemes that are robust to such scenarios. In particular, the simplest case is considered whereby one has available attenuation measurements with associated measurement errors at discrete points in time. From these discrete, "noisy" observations of link attenuation, it is necessary to obtain optimal estimates of not only the satellite link attenuation that corresponded to the measurement, but also an optimal prediction of what the attenuation value will be at the next (future) sampling time. This problem is formed within the context of nonlinear Markov filtering. The optimality criterion used will be the minimization of the least square error that exists between the predicted value of attenuation and that estimated from the noisy measurement process. The only fading mechanism that will be considered is that due to rain; scintillation and other simultaneous signal power impairments can also be considered, but at the expense of a much more complicated and involved exposition.

Dynamics Portion of the ACTS Rain Attenuation Prediction Model

From the development of the ACTS Rain Attenuation Prediction Model (in particular, Section 5 of [1]), one models the temporal evolution of the link attenuation $A(t)$ through the parameter $x_A(t)$:

$$x_A(t) = \frac{\ln A(t) - \ln A_m}{\sigma_{\ln A}} \qquad (1)$$

where A_m is the median of the link attenuation and $\sigma_{\ln A}$ is the standard deviation of the logarithm of attenuation; these two parameters are specific to the particular location, frequency of operation and geometry of the satellite link. It is the $x_A(t)$ parameter that is given by, in the most general case, a multicomponent Markov random process which is determined by a system of first-order stochastic differential equations. It is, however, expedient to reduce to

a one-component model with careful consideration given to the incorporation of the temporal smoothing process induced by the extended propagation path. In particular, as was done in [1], one can approximately consider the one-component process given by the single first-order differential equation

$$\frac{dx_A}{dt} = -\gamma_S x_A + \sqrt{2\gamma_S}\,\xi(t) \qquad (2)$$

where the random function $\xi(t)$ is governed by Gaussian statistics with a zero mean (i.e., "white noise"):

$$\langle \xi(t) \rangle = 0\,, \quad \langle \xi(t)\xi(t+\tau) \rangle = \delta(\tau)$$

and where γ_S is a "smoothed" temporal parameter that is given by the solution of the transcendental equation

$$exp\left(-\frac{\gamma_1}{\gamma_S}\right) + exp\left(-\frac{\gamma_2}{\gamma_S}\right) = exp(-1) \qquad (3)$$

From geometrical considerations concerning the propagation path, characteristic rain cell size and long term spatial isotropy of rain cell movement, one has the following relation that exists between the coefficients γ_1 and γ_2 that appear in Equation (3):

$$\gamma_2 = \gamma_1\left(1 + \frac{2L\cos\theta}{\pi R_C}\right)^{-1/2} \qquad (4)$$

where L is the total propagation path length within the potential rain region, θ is the link elevation angle and $R_C = 4$ km is the characteristic rain cell size as required by fundamental considerations and model constraints [1]. By the same considerations, one has for the coefficient γ_1

$$\gamma_1 = \frac{2v}{\pi R_C} \approx 0.1336 \text{ min}^{-1} \qquad (5)$$

where $v = 14$ m/sec is the characteristic speed of the rain cell that is assumed in the model. For a typical communications link with an elevation angle ~40 deg, $\gamma_S \sim 0.06$ min^{-1} = 0.001 sec^{-1}.

In what follows, the one-component Markov process $x_A(t)$ given by Equation (2), with contact made to the link attenuation $A(t)$ through Equation (1), will be used to derive an optimal fade detection and prediction algorithm for use with measured (real time) fade data.

Development of an Optimal Fade Identification and Prediction Algorithm

Synthesis of the Models of Observation, Random Process and Measurement Uncertainty

Here, the problems of fade identification and prediction as defined in the introduction will be rigorously defined. At the outset, it is useful to consider the measurement process via the following *observation model*:

$$A_{obs}(t) = A(t) + n(t) \qquad (6)$$

where $A(t)$ is the actual attenuation that exists on the communications link at time t, $n(t)$ is the associated measurement uncertainty or "noise" and $A_{obs}(t)$ is the observed link attenuation. The measurement noise — which can result from inaccuracies in the hardware of the measurement process or from an assumed measurement function such as that used in "frequency scaling," whereby a signal fade at one

frequency is derived from a fade measurement at another frequency — is a random function of time and can, at least at the outset, be statistically characterized by a Gaussian white noise process — the *measurement uncertainty model*:

$$\langle n(t)\rangle = 0$$
$$\langle n(t_1)n(t_2)\rangle = \sigma_n^2\,\delta(t_1 - t_2) \qquad (7)$$

where σ_n is the standard deviation of the measurement noise. Remembering Equation (1), one has from Equation (6),

$$A_{obs}(t) = A(x_A,t) + n(t)\ ,\ A(x_A,t) \equiv A_m\,exp\left(\sigma_{lnA}\,x_A(t)\right) \qquad (8)$$

for the observation model where the random process x_A is governed by the stochastic differential equation Equation (2). In this context, Equations (1) and (2) make up the *process model* to which the observation model of Equation (6) is applied. The following problem can now be defined: Given the measured fade $A_{obs}(t)$ connected, via the observation model of Equation (6), to the process $A(t)$ — the model of which is through Equations (1) and (2) and the consequences of these relationships given by Equation (8) — and given the statistics which govern the measurement errors, Equation (7), it is desired to obtain an estimate of the quantity $x_A(t)$ at time t (i.e., identification) as well as the extrapolated estimate of the quantity $x_A(t+\tau)$ that should prevail at a future time $t+\tau$ (i.e., prediction). Using Equation (1), one can then easily obtain the corresponding values $A(t)$ and $A(t+\tau)$. This is formally a problem in the optimal (with respect to a given criterion) estimation (or filtering) and prediction of a nonlinear Markov continuous random process sampled in time.

The Need for A Posteriori Probability Densities and Optimal Estimates of a Time-Sampled Continuous Random Process

Since the random process in question is the quantity x_A and it is desired to obtain information concerning the instantaneous value of this quantity from the measurement of A_{obs}, one must invariably deal with a parameter known as the a posteriori probability density $p\,(x_A(t) \mid A_{obs}(t))$ governing the random process at a time t conditioned on the observation of the quantity $A_{obs}(t)$. Once this probability density has been secured, one can easily obtain descriptions of the random process x_A in the form of statistical moments such as the average $x_A^*(t)$ (referred to as the *optimal estimate* minimized with respect to the mean-square error), the associated standard deviation $\sigma^*_{x_A}(t)$ of the optimal estimate, etc.

Although both $x(t)$ and $A_{obs}(t)$ are, in general, continuous in the time variable, the latter is actually sampled at discrete times t_i with a corresponding time interval T separating the samples, i.e., $T = t_i - t_{i-1}$. Thus, due to this sampling process overlaid on the continuous process $A_{obs}(t)$, one must also now consider additional random processes which result from the sampling:

$$\tilde{A}_{obs}(t_i) = A_{obs}(t)\,\delta(t - t_i)$$
$$\tilde{x}_A(t_i) = x_A(t)\,\delta(t - t_i) \qquad (9)$$

One must thus amend the a posteriori probability density $p\,(x_A(t) \mid A_{obs}(t))$ to reflect this circumstance and consider $p\,(x_A(t), \tilde{x}_A(t) \mid A_{obs}(t))$ — the probability density governing the continuous random process $x_A(t)$ and the sampled process $\tilde{x}_A(t)$ conditioned on the value of the discrete measurement of $A_{obs}(t)$.

Statistical Identification of Prevailing Link Attenuation Level

Now the random process $x_A(t)$, described by Equation (2), has associated with it a transition (and conditional) probability density $p\,(x_A(t) \mid \tilde{x}_A(t_i))$, giving the statistics connected with the evolution of the sampled value $\tilde{x}_A(t_i)$ at a time t_i to the value of its

continuous counterpart $x_A(t)$ at a later time $t > t_i$. Following the results in [1] [in particular, Eqs. (53) and (54)], this transition probability density is given by the Kolmogorov equation associated with the first-order differential equation, Equation (2):

$$\frac{\partial p\left(x_A(t) \mid \tilde{x}_A(t_i)\right)}{\partial t} = D_{x_A}\left[p\left(x_A(t) \mid \tilde{x}_A(t_i)\right)\right], \quad t > t_i \tag{10}$$

where the differential operator $D_{x_A}[f(x_A)]$ for the Kolmogorov equation is given by

$$D_{x_A}[f(x_A)] \equiv \gamma_S \frac{\partial}{\partial x_A}\left(x_A f(x_A)\right) + \gamma_S \frac{\partial^2 f(x_A)}{\partial x_A^2} \tag{11}$$

In an analogous fashion, the probability density $p(x_A(t), \tilde{x}_A(t) \mid A_{obs}(t))$ is a transition probability density governing the random processes $x_A(t)$ and $\tilde{x}_A(t)$ conditioned on the set of measured observations $A_{obs}(t)$, each of which is connected with the random process in question via the observation model of Equation (6) and the sampling model of Equation (9). In this case, the Kolmogorov equation of Equation (10) must be modified with this (nonlinear) observation model. In particular, amending the observation model of Equation (6) with the sampling model of Equation (9), one has that the quantity

$$n(t) = \tilde{A}_{obs}(t) - A(\tilde{x}_A, t) \tag{12}$$

is a zero mean Gaussian random variable with variance σ_n^2 [by Equation (7)]. It is desired to augment the dynamic description of the random process $x_A(t)$ that is afforded by the Kolmogorov equation, Equation (10), with observed a priori measurements $A_{obs}(t_i)$ of the link attenuation which, through Equation (8), is a convolution of $\tilde{x}_A(t_i)$ as well as the measurement noise $n(t)$. In this instance [2,3], one must employ a modified version of the Stratonovich Equation [4], well known in Markov filtering theory:

$$\frac{\partial p\left(x_A(t), \tilde{x}_A(t) \mid A_{obs}(t_i)\right)}{\partial t} = D_{x_A}\left[p\left(x_A(t), \tilde{x}_A(t) \mid A_{obs}(t_i)\right)\right] + \left[\phi\left(\tilde{x}_A(t), t_i\right) - \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \phi\left(\tilde{x}_A'(t), t_i\right) p\left(x_A'(t), \tilde{x}_A'(t) \mid A_{obs}(t_i)\right) d\tilde{x}_A' dx_A'\right] \times p\left(x_A(t), \tilde{x}_A(t) \mid A_{obs}(t_i)\right) \tag{13}$$

where

$$\phi\left(\tilde{x}_A(t), t_i\right) \equiv -\frac{1}{2\sigma_n^2}\left(A_{obs}(t_i) - A(\tilde{x}, t_i)\right)^2 \tag{14}$$

It is important to note that Equation (13) holds for times t within the interval $t_i < t < t_{i+1}$.

The solution of the integrodifferential Equation (13) commences with writing the a posteriori probability density in the form

$$p\left(x_A(t), \tilde{x}_A(t) \mid A_{obs}(t_i)\right) = p\left(x_A(t) \mid \tilde{x}_A(t)\right) p\left(\tilde{x}_A(t) \mid A_{obs}(t_i)\right) \tag{15}$$

The result of the ensuing straightforward analysis [2,3] involving the well established Gaussian approximation for such problems, and evoking the optimality criterion that minimizes the mean-square error for the *optimal estimate* $x^*(t_i)$ of the value of $\tilde{x}_A(t_i)$ connected with the observational data $A_{obs}(t_i)$,

$$x_A^*(t_i) = \int_{-\infty}^{\infty} \tilde{x}_A(t_i)\, p\left(\tilde{x}_A(t_i) \mid A_{obs}(t_i)\right) d\tilde{x} \qquad (16)$$

yields the following recursive calculational algorithm involving the *extrapolated estimate* $\hat{x}_A(t)$ of the random process $x_A(t)$ available at time t, the *error covariance* of the optimal estimate $\sigma^*_{x_A}(t_i)$ and the *standard deviation* (or, in general, the covariance) associated with the errors of the extrapolated estimate $K(t)$:

$$\begin{aligned} x_A^*(t_i) &= \hat{x}_A(t_i) + \sigma^*_{x_A}(t_i)\, a(t_i) \\ \hat{x}_A(t_i) &= \Phi_i x_A^*(t_{i-1}) \\ \sigma^*_{x_A}(t_i) &\equiv \left(K^{-1}(t_i) - b(t_i)\right)^{-1} \\ K(t_i) &= 1 + \Phi_i^2\left(\sigma^*_{x_A}(t_{i-1}) - 1\right) \end{aligned} \qquad (17)$$

where the coefficients $a(t_i)$ and $b(t_i)$ are defined by

$$a(t_i) \equiv \left.\frac{\partial \phi_s(\tilde{x}, t_i)}{\partial \tilde{x}}\right|_{\tilde{x}=\hat{x}}, \quad b(t_i) \equiv \frac{1}{2}\left.\frac{\partial^2 \phi_s(\tilde{x}, t_i)}{\partial \tilde{x}^2}\right|_{\tilde{x}=\hat{x}} \qquad (18)$$

and contain the observed sampled values $A_{obs}(t_i)$ through the identification $\phi_s(\tilde{x}_A(t_i), t_i) \equiv \phi(\tilde{x}_A(t), t)\delta(t-t_i)$. Thus, using Equation (14), one has

$$\begin{aligned} a(t_i) &= \left(\frac{\sigma_{lnA}}{\sigma_n^2}\right) A(\hat{x}, t_i)\left(A_{obs}(t_i) - A(\hat{x}_A, t_i)\right) \\ b(t_i) &= \left(\frac{\sigma_{lnA}^2}{\sigma_n^2}\right) A(\hat{x}, t_i)\left(A_{obs}(t_i) - 2A(\hat{x}_A, t_i)\right) \end{aligned} \qquad (19)$$

Also, in Equation (17), $\phi_i \equiv \exp(-\gamma_S(t_i - t_{i-1}))$ is the temporal transition parameter for the process between consecutive sampling instants t_{i-1} and t_i.

The time discrete and recursive relations of Equation (17), in addition to the auxiliary relations of Equation (19), collectively compose the dynamic identification part of the problem defined at the outset. The approximation used, as well as considerations of the errors incurred in the optimal estimate, places upper limits on the time interval (t_{i-1}, t_i) between consecutive samples. However, the typical clock intervals of ~1 sec that are encountered in practice are easily within this limit. It now remains to obtain a prescription for the dynamic prediction of link fade levels into the future based on the data afforded from this fade identification process.

Prediction of Link Attenuation for Short Times Into the Future

From some results of the foregoing, in particular the solution from the attendant Kolmogorov equation for the transition probability density of the attenuation process, one can derive a relation yielding the average value of the link attenuation at a time T_{pred} into the future. In particular, the problem can be succinctly defined as follows: Given the fact that an optimal estimate $x_A^*(t_i)$ is obtained for the attenuation process at the time t_i, and *on the hypothesis that the attenuation will increase*, it is of interest to obtain the extrapolated estimate $\widehat{\Delta x_A}(t_i + T_{pred})$ of the change in the attenuation that will occur at a later time $t_i + T_{pred}$. One then has for the total value of this combined extrapolated optimal estimate of the attenuation process

$$\widehat{x_A^*}(t_i + T_{pred}) = x_A^*(t_i) + \widehat{\Delta x_A}(t_i + T_{pred}) \qquad (20)$$

By this formulation of the problem, one obtains for the extrapolated optimal estimate of attenuation for a future time $t_i + T_{pred}$ based on the estimate at time t_i

$$\widehat{x_A^*}(t_i + T_{pred}) = \Psi_{pred}\, x_A^*(t_i) + \frac{D(T_{pred})}{4} \qquad (21)$$

where

$$\Psi_{pred} \equiv 1 - \sqrt{\frac{D(T_{pred})}{2\pi}}\left(1 - \Phi_{pred}\right) \qquad (22)$$

$$\Phi_{pred} \equiv exp\left(-\gamma_S\, T_{pred}\right) \qquad (23)$$

and

$$D(T_{pred}) \equiv 1 - \Phi_{pred}^2 \qquad (24)$$

A limitation is placed upon the maximum value of T_{pred} by an approximation used to obtain Equation (21); in particular, one has

$$T_{pred} << \frac{\sigma_{lnA}}{2\gamma_S\left(ln\, A(t) - ln\, A_m\right)}$$

showing that, as can be expected, the value is a function of the prevailing link attenuation $A(t)$. A more rigorous analysis for this maximum value would involve considering the prediction error associated with $\widehat{\Delta x_A}(t_i + T_{pred})$. However, since in the applications one usually only needs to predict no more than 2 to 4 time intervals ahead (i.e., typically ~2 to 4 sec), this condition is easily met.

Algorithmic Implementation of the Foregoing Discussion

The synthesis of the relevant relations derived in the foregoing discussion is shown in Figure 1

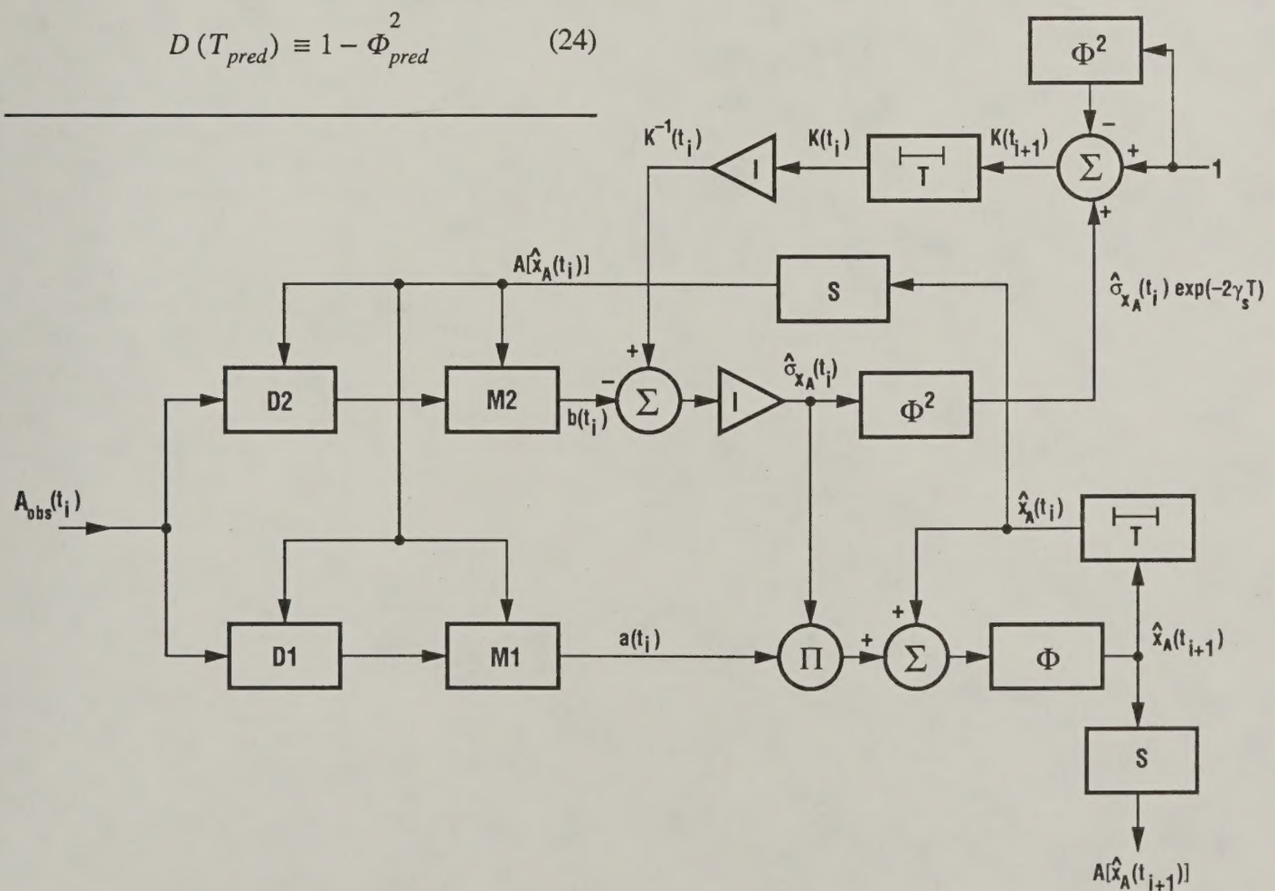

Figure 1. Synthesis of the mean-square optimal rain fade identification and prediction processor.

and comprises two separate sections: one that performs fade identification and one that performs fade prediction. In the identification section, ***D1*** and ***D2*** perform as discriminators carrying out the operations $[A_{obs}(t) - A(\hat{x}_A(t_i))]$ and $[A_{obs}(t) - 2A(\hat{x}_A(t_i))]$, respectively; multipliers ***M1*** and ***M2*** form the operations needed to complete the emulation of the relations given in Equation (19); the inverters ***I*** perform multiplicative inversion, and ***S*** denotes the emulation of the operation yielding $A_m \exp(\sigma_{lnA} x_A(t))$. Also, ϕ_i denotes the multiplication by the discrete time transition factor $\exp(-\gamma_S T_i)$, ϕ_i^2 is the square of this factor and T_i is a time delay of T_i seconds. In the prediction section, once a time interval T_{pred} is selected over which a fade prediction is to be made, $D(T_{pred})$ evaluates the operation $1 - \exp(-2\gamma_S T_{pred})$, ψ_{pred} then performs the operation as specified by Equation (22) and finally multiplier ***M3*** forms the second member of the right side of Equation (21).

Such an algorithm can be implemented either in software or hardware and is easily included in the operation of any satellite Earth station. Although the *structure* of the algorithm remains the same in every application, several of the numerical coefficients which it employs reflect the specific geometry and operating frequency of a satellite link as well as the location of the Earth terminal. For example, γ_S is a function of the propagation path length through the potential rain region as well as of the elevation angle, as shown by Equation (4). Not only is the link operating frequency reflected in the selection of the parameters A_m and σ_{lnA} that appear in each ***S*** module of Figure 1, but also the specific location of the Earth station due to the extremely detailed rain statistics database of the ACTS rain attenuation model (a geographical resolution of ~0.5 deg in latitude and longitude in the continental United States, essentially equivalent to about 6,000 rain "zones") from which they are calculated. The software implementation of the ACTS Rain Attenuation Prediction Model for this and other general satellite system link designs is available from COSMIC, NASA Software for Industry, University of Georgia, Athens, GA 30602.

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